



Life cycle assessment of poplar production: Environmental impact of different soil enrichment methods

Michał Krzyżaniak ^{a, b, *}, Mariusz Jerzy Stolarski ^{a, b}, Kazimierz Warmiński ^{b, c}

^a Department of Plant Breeding and Seed Production, University of Warmia and Mazury in Olsztyn, ul. Oczapowskiego 2, 10-719 Olsztyn, Poland

^b Centre for Bioeconomy and Renewable Energies, University of Warmia and Mazury in Olsztyn, ul. Oczapowskiego 2, 10-719 Olsztyn, Poland

^c Department of Chemistry, Research Group of Environmental Toxicology, University of Warmia and Mazury in Olsztyn, ul. Oczapowskiego 2, 10-719 Olsztyn, Poland

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ABSTRACT

The bioeconomy is expected to play an important role in the low carbon economy and poplar could be one of the species providing lignocellulosic feedstock for bioindustries. Since mineral fertilizers are expensive, alternative methods of plant fertilisation are currently being sought. Therefore, the aim of this study was to determine the environmental impact of the production of poplar grown on poor mineral soil fertilized with mineral fertilizers (F), lignin (L) and mineral fertilizers plus lignin (LF) and unfertilized (C) using a life cycle assessment. The system boundaries embraced the production and use of fertilizers, agricultural operations and field emissions associated with poplar cultivation (from cradle to farm gate). Negative greenhouse gases (GHG) emission was observed in variants: L ($-37.0 \text{ kg Mg}^{-1} \text{ d.m. CO}_2 \text{ eq.}$) and LF ($-20.6 \text{ kg Mg}^{-1} \text{ d.m. CO}_2 \text{ eq.}$). The emission in variant C was $25.2 \text{ kg Mg}^{-1} \text{ d.m. CO}_2 \text{ eq.}$ In all of the cultivation variants except C, a very high normalized score was determined for freshwater eutrophication, followed by variants L and LF in categories: freshwater and human ecotoxicity. A low impact of poplar cultivation was determined for fossil depletion and terrestrial ecotoxicity. A low normalized score was also calculated for climate change. The analyses indicated that lignin can be recommended as the optimum method of fertilisation. Using only mineral fertilizers is slightly less beneficial for the environment. Variant LF is not recommended due to the high impact on freshwater eutrophication, terrestrial acidification, human and freshwater ecotoxicity and depletion of fossil resources.

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1. Introduction

According to the OECD, the bioeconomy will involve three elements: advanced knowledge of genes and complex cell processes, renewable biomass and the integration of biotechnology applications across sectors. It is assumed that the bioeconomy will be global, with large involvement from OECD and non-OECD countries, especially in agriculture and industry (OECD, 2009). The bioeconomy is expected to play an important role in the low carbon economy in European Union, as well. Europe has a number of well-established traditional bio-based industries, ranging from

agriculture, food, feed, fibre and forest-based industries. Scarlat et al. (2015) estimated that the current bioeconomy market is worth €2.4 billion and includes agriculture, food, agro-industrial products, fisheries and aquaculture, forestry, wood-based industry, biochemical, enzymes, biopharmaceutical, biofuels and bioenergy. These bioeconomy branches employ approx. 22 million people (Golembiewski et al., 2015).

High-value bioproducts can be made from lignocelluloses. Speciality cellulose is used in the manufacturing of cosmetics, textiles, pharmaceutical, tires, ethanol and more. Hemicelluloses are also used in the production of ethanol and furfural. Lignin can be potentially used as a feedstock for manufacturing high-value products, e.g. vanillin, biopolymers in petro-chemistry, pesticides and others, including as material for soil enrichment, especially poor sandy sites. Obviously, lignocellulosis can be used successfully - as it has been - in the generation of electricity and heat (Bozell and Petersen, 2010; Doherty et al., 2011; Serrano et al., 2012; Sjöde, 2013; Stolarski et al., 2016b).

* Corresponding author. Department of Plant Breeding and Seed Production, University of Warmia and Mazury in Olsztyn, ul. Oczapowskiego 2, 10-719 Olsztyn, Poland.

E-mail addresses: michal.krzyzaniak@uwm.edu.pl (M. Krzyżaniak), mariusz.stolarski@uwm.edu.pl (M.J. Stolarski), kazimierz.warmiński@uwm.edu.pl (K. Warmiński).

Abbreviations

C input	carbon input	kg Mg ⁻¹ d.m. P eq.	kilogram of phosphorus equivalents per megagram of dry matter (dry biomass)
C	unfertilized variant (control)	kg Mg ⁻¹ d.m. PM10 eq.	kilogram of particulate matter (10 µm or less in diameter) equivalents per megagram of dry matter (dry biomass)
C:N	carbon to nitrogen ratio	kg Mg ⁻¹ d.m. SO ₂ eq.	kilogram of sulphur dioxide equivalents per megagram of dry matter (dry biomass)
C _{above}	aboveground carbon in crop residues (kg ha ⁻¹ C)	L	lignin variant
C _{above_Poplar}	aboveground carbon in poplar crop residues (kg ha ⁻¹ C)	LCA	Life Cycle Assessment
C _{above_Ref}	aboveground carbon in reference crop residues (kg ha ⁻¹ C)	Mg ha ⁻¹ d.m.	megagram of dry matter per hectare
C _{below}	belowground carbon in root residues (kg ha ⁻¹ C)	Mg ha ⁻¹ f.m.	megagram of fresh matter per hectare
C _{below_Poplar}	belowground carbon in poplar root residues (kg ha ⁻¹ C)	LF	mineral fertilizers plus lignin variant
C _{below_Ref}	belowground carbon in reference root residues (kg ha ⁻¹ C)	N ₂	nitrogen gas
CH ₄	methane	N ₂ O	nitrous oxide
C _{lignin}	lignin organic carbon (kg ha ⁻¹ C)	N _{AD}	precipitation nitrogen deposition (kg ha ⁻¹ N)
CO ₂	carbon dioxide	NH ₃	ammonia
EF _{default}	default emission factor	NMVOC	non-methane volatile organic compounds
EF _{TS}	technology-specific emission factor	NO _x	nitrogen oxides (NO and NO ₂)
F	mineral fertilizers variant	NPK	nitrogen, phosphorus, potassium
FU	functional unit	NPV	net present value
GHG	greenhouse gases	OECD	Organisation for Economic Co-operation and Development
IPCC	Intergovernmental Panel on Climate Change	OM	organic matter
IRR	internal rate of return	PM10	particulate matter less than 10 µm
ISO	International Organisation for Standardization	PM2.5	particulate matter less than 2.5 µm
kg ha ⁻¹ C	kilogram of carbon per hectare	R _{AG}	ratio of above-ground residues dry matter to harvested yield d.m. for crop
kg GJ ⁻¹ CO ₂ eq.	kilogram of carbon dioxide equivalents per gigajoule of energy in fresh biomass	R _{BG}	ratio of below-ground residues dry matter to harvested yield d.m. for crop (root:shoot ratio)
kg ha ⁻¹ year ⁻¹ CO ₂ eq.	kilogram of carbon dioxide equivalents per hectare per year	SOC	soil organic carbon
kg Mg ⁻¹ d.m. 1,4-DB eq.	kilogram of 1,4-dichlorobenzene equivalents per megagram of dry matter (dry biomass)	SRC	short rotation coppice
kg Mg ⁻¹ d.m. CO ₂ eq.	kilogram of carbon dioxide equivalents per megagram of dry matter (dry biomass)	UWM	University of Warmia and Mazury in Olsztyn, Poland
kg Mg ⁻¹ d.m. oil eq.	kilogram of oil equivalents per megagram of dry matter (dry biomass)	α	harvest index of main crop product relative to aboveground biomass
		β	root biomass carbon as proportion of yield of main crop product
		ε	concentration of carbon in biomass (kg C Mg ⁻¹ d.m.)

One of the species that provides lignocellulosic feedstock is poplar (*Populus* spp.). It includes 40–100 species and hundreds of cultivars grown all over the northern hemisphere; they can be cultivated both as a forest crop in long rotations (10–20 years) and as short rotation coppices (SRC) (2–5 years) (Barontini et al., 2014; Johansson and Karačić, 2011). Poplar yields (according to various authors) from 2 up to 25 Mg ha⁻¹ year⁻¹ d.m. (Guidi et al., 2009; Guo and Zhang, 2010; Johansson and Karačić, 2011; Stolarski et al., 2015). The yield depends on a number of factors such as climate, soil, cultivar, planting density and rotation. Moreover, intensification is often a priority in the cultivation of poplar in short rotations. Irrigation, plant protection products and fertilisation is used in high-yield production technologies (Dimitriou and Mola-Yudego, 2017; Grella et al., 2017; Paris et al., 2018; Schweier et al., 2016; Yan et al., 2018). Since mineral fertilizers are expensive and their use in plantations of perennial energy crops is not always effective, alternative fertilisation methods are sought using waste materials, i.e. sewage sludge, animal manure, compost, biochar and others. The benefits of organic fertilizers include - apart from supplying nutrients to plants - improvement of soil fertility and fixing organic carbon in soil (Buss et al., 2016; Lafleur et al., 2012; Moreno et al., 2017). Therefore, a team of researchers at the University of

Warmia and Mazury in Olsztyn is studying the use of alternative methods of fertilisation and soil enrichment in plantations of perennial lignocellulosic plants. The findings of studies have already been reported concerning the effect of fertilisation with various forms of biogas digestate on the yield of herbaceous crops, i.e. Jerusalem artichoke, giant miscanthus, willow leaf sunflower and Virginia mallow (Stolarski et al., 2017a). Studies have been conducted on the use of lignin for fertilisation of plantations of willow, poplar and black locust and found that the use of lignin usually increases the yield and has a beneficial effect on the economic and energy balance of lignocellulosic biomass production of these three crops (Stolarski et al., 2016a, 2017a). Scientific literature on crop production indicates that the application of mineral fertilisation is one of the main sources of emission to the environment. For instance, Gasol et al. (2009) found that in poplar production, the highest environmental impact was connected with the production and use of fertilizers, representing 51–67% of global warming, fresh water aquatic ecotoxicity, marine aquatic ecotoxicity and terrestrial ecotoxicity. Heller et al. (2003) reports that fertilizers constituted 75% of the greenhouse gas emissions included in agricultural inputs of willow production. The mineral fertilizers were also the main agricultural input with the highest environmental impact for

sunflower and rape production (Iriarte et al., 2010). In sunflower, the contribution of mineral fertilizers was more than 55% in 7 of the 11 impact categories; in rapeseed their contribution was between 74% and 99% in all but one category. Industries associated with bioeconomy are paying particular attention to the reduction of greenhouse gas emission from feedstock production (e.g. ligno-cellulosic crops). In principal, although the application of varied organic residues results in the reduction of emissions, it may lead to other undesirable environmental effects such as a several-fold increase in eutrophication or acidification (Heller et al., 2003; Krzyżaniak et al., 2018; Murphy et al., 2013). Therefore, the present study aims not only at issues related to carbon footprint, but also at understanding the comprehensive effect on the environment of the application of organic residues and fertilisers in agricultural production. The aim of this study was to determine the environmental impact of cultivating and harvesting poplar trees grown on poor mineral soil fertilized with mineral fertilizers, lignin and unfertilized, using a life cycle assessment.

2. Methods

In order to determine the environmental impact of the production of poplar, the study methodology was based on the standards: ISO 14040 “Environmental management – Life cycle assessment – Principles and framework” and ISO 14044 “Environmental management – Life cycle assessment – Requirements and guidelines” (Standardization, 2006a, 2006b). A life cycle assessment was conducted with SimaPro software.

2.1. Goal, scope and functional unit

This study analysed the environmental impact of the cultivation and harvesting of poplar trees grown on poor mineral soil fertilized with mineral fertilizers, lignin and unfertilized (base scenario). The research system boundary “from cradle to farm gate” was adopted. 1 Mg of dry biomass was taken as a functional unit (FU). In order to illustrate the GHG emission, 1 ha of poplar plantation and 1 GJ of energy in fresh biomass was adopted as the FU.

2.2. System boundaries

The system boundaries covered the production and use of mineral fertilizers and lignin, agricultural operations, growing poplar, harvesting and chipping up the wood and transport of chips from the field to the farm (from cradle to farm gate) (Fig. 1). The plantation use period was assumed to be 20 years. A detailed description of the system boundaries is presented in the following subchapters.

2.2.1. Poplar production

The study was based on a field trial carried out from 2010 to 2013 at a research station owned by the University of Warmia and Mazury in Olsztyn (Poland) (53°59' N, 21°04' E). The trial was run on Brunic Arenosol (Dystric) soil formed from loose sand. Detailed data on the soil, weather and the field protocol are presented in the paper (Stolarski et al., 2015).

Poplar (*Populus nigra* × *Populus maximowiczii* Henry cv. Max-5) cuttings were planted in twin-row design with a spacing of 75 cm within twin rows with 150 cm between pairs of rows. Cuttings were spaced 80 cm apart within the rows. The final planting density was 11,000 ha⁻¹.

The method of soil enrichment included: application of lignin (L), mineral fertilisation (F), lignin + mineral fertilisation (LF) and control (C) without soil enrichment or mineral fertilisation.

Lignin was applied at 13.3 Mg ha⁻¹ in spring 2010 before the

experiment was set up. It was scattered on the soil with a spreader. The lignin contained 61.72% organic matter (OM).

Mineral fertilisation was applied before the beginning of the second year of plant growth (2011). Phosphorus (P₂O₅) was applied at 30 kg ha⁻¹ as triple superphosphate and potassium (K₂O) at 60 kg ha⁻¹ was applied as potassium salt. Nitrogen was applied as ammonium nitrate in two doses: at 50 kg ha⁻¹, immediately before the plant growth in 2011 and 40 kg ha⁻¹ in mid-June 2011.

The following procedures were performed once: spraying with glyphosate, winter ploughing, lignin fertilisation, disking (x2), harrowing (2x), marking spots for planting, manual planting, chemical weeding, mechanical weeding (3x) and plantation liquidation. Procedures were performed after each rotation (every four years) throughout the plantation's life cycle: mineral (NPK) fertilisation, harvesting and transport to a farm for the distance of 5 km. The cultivation system was based on data collected from a field experiment and data obtained in other experiments carried out at UWM, catalogues of machines and devices and the EcoInvent database (Table 1).

2.2.2. Production of fertilizers

The study system boundary embraced the production of lignin as waste in paper production in the kraft process.

Inventory data on the production of 1 kg of untransformed kraft lignin was taken from Bernier et al. (2013). The share of electricity mix was adopted for the conditions of Poland and the transport distance from the production facility to the farm was adopted as 30 km. Since lignin used as fertilizer does not require additional drying, apart from air-drying, this stage was omitted.

Data for mineral fertilizers included inputs incurred for production ammonium nitrate (34% N), triple superphosphate (48% P₂O₅) and potassium chloride (60% K₂O). The data were obtained from the EcoInvent database.

2.2.3. Field emissions

Field emissions of GHG are the sum of depletion of soil organic carbon (SOC) (emission of CO₂), emission of CH₄ from soil (anaerobic SOC transformations) and N₂O emissions being a result of nitrification and denitrification of nitrogen. An increase in SOC content is the negative emission of CO₂. Emission of CH₄ was taken as equal to zero, because poplar was grown on mineral, not marshy soil (Eggleston et al., 2006). SOC change (net C input) was calculated as a difference between organic carbon (OC) available to the soil from poplar and a reference crop. The reference crop was spring barley with straw incorporated into the soil (Krzyżaniak et al., 2018; Parajuli et al., 2017a, 2017b). The available OC in the current study originated from aboveground and underground crop residues (C_{above}, C_{below}), and, in the case of poplar, from fertilisation with lignin (C_{lignin}). Net C input (kg ha⁻¹ C) was calculated from the formula:

$$\text{Net C input} = C_{\text{above_Poplar}} + C_{\text{below_Poplar}} + C_{\text{lignin}} - C_{\text{above_Ref}} - C_{\text{below_Ref}}$$

OC from crop residues was calculated according to the C-TOOL model (Taghizadeh-Toosi et al., 2014) from the equations:

$$C_{\text{above}} = (1/\alpha - 1)eY$$

$$C_{\text{below}} = \{\beta / [(1 - \beta)\alpha]\}eY$$

The equation parameters for both crops and their explanations are provided in Table 3. Calculations of the parameters α and β for poplar were based on the authors' field experiment data (woody biomass yield and the mass of leaf litter), content of C and the

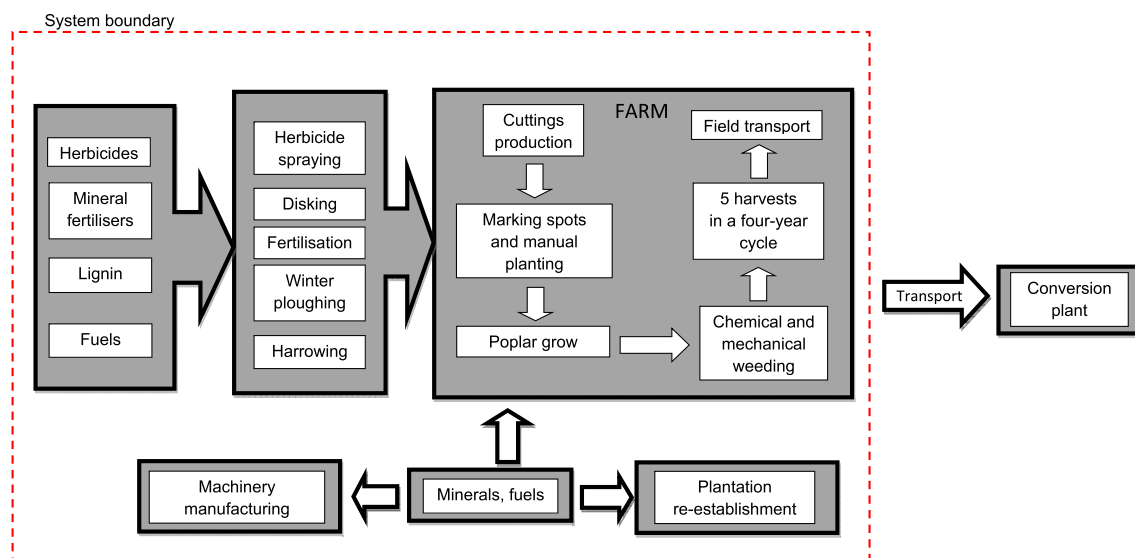


Fig. 1. System boundary of poplar cultivation, harvest and transport.

root:shoot ratio. The carbon content in poplar (ϵ) and in the leaf litter was determined with the use of an elemental analyser ELTRA CHS 500 (ELTRA GmbH, Germany). The amount of C_{lignin} was calculated taking the dose of lignin applied and the OC content (Table 3). A positive net input of OC results in an increase in the SOC content. It was assumed in the analysis that only 9.7% of the net C input was sequestered (Petersen et al., 2013).

Apart from SOC change, the analysis of GHG emissions takes into account the direct emission of N_2O (emission of N_2O from soil), as well as indirect emission. Indirect N_2O emission is associated with leaching of nitrates from soil as well as with emission of NH_3 and NO_x . Subsequently, these nitrogen species are transformed in the environment to N_2O at a rate of approx. 0.75–1% (Table 3). Emissions of N_2O were calculated by the method recommended by IPCC (Eggleston et al., 2006).

The nitrate leaching was calculated by the field N-balance method, taking into account the dose of N in the fertilizers, atmospheric deposition of N, the net annual amount of N mineralized in soils as a result of loss of soil carbon, N in the harvested crop and gas emission from soil (NH_3 , NO_x , N_2O , N_2). The balance method has also been applied by other authors (Alaphilippe et al., 2016; Parajuli et al., 2017a, 2017b). N_2 emission from soil was calculated based on the SimDen model (Vinther, 2005). Emission of NH_3 , NO_x and PM10, PM2.5, NMVOC was calculated by the index method recommended by the European Environment Agency (2016), adopting the default or technology-specific emission factors. In turn, phosphate leaching from fertilizers was calculated adopting the index given by Iriarte et al. (2010). The values of parameters used in this study are given in Table 3 and the procedures applied are described in detail by Krzyżaniak et al. (2018).

2.3. Life cycle impact assessment

The life cycle impact assessment of poplar cultivation was determined by the ReCiPe Midpoint (H) method, including the midpoints, of which eight categories of environmental impact were selected which were closely connected with agricultural production: climate change in carbon dioxide equivalents (CO_2 eq.), human toxicity in 1,4-dichlorobenzene equivalents (1,4-DB eq.), particulate matter formation in particulate matter, 10 μm equivalents (PM10 eq.), terrestrial acidification in sulphur dioxide

equivalents (SO_2 eq.), freshwater eutrophication in phosphorus equivalents (P eq.), terrestrial ecotoxicity and freshwater ecotoxicity (both in 1,4-DB eq.) as well as fossil depletion in crude fossil oil equivalents (oil eq.). The ReCiPe impact categories were narrowed down based on other studies on perennial crops (Bessou et al., 2013; Dressler et al., 2012; Krzyżaniak et al., 2018). After entering inputs and outputs into the SimaPro program, calculations were made of the environmental impact (characterisation). In order to compare which categories of impact had the most adverse effect on the environment during the production of poplar biomass, they were reduced to the same unit by normalization (Europe ReCiPe H/H).

3. Results

3.1. Characterisation results

Net emission of GHG (taking into account organic carbon sequestration at $61 \text{ kg ha}^{-1} \text{ year}^{-1} \text{ CO}_2 \text{ eq.}$) from poplar cultivation, without fertilisation (C), was $138 \text{ kg ha}^{-1} \text{ year}^{-1} \text{ CO}_2 \text{ eq.}$ (Table 4). When calculated per 1 Mg of dry biomass and 1 GJ of energy in biomass, it was $25.17 \text{ kg Mg}^{-1} \text{ CO}_2 \text{ eq.}$ and $1.49 \text{ kg GJ}^{-1} \text{ CO}_2 \text{ eq.}$, respectively (Fig. 2). The largest contribution to emission of carbon dioxide equivalents was calculated for biomass harvest with a forage harvester (58.8%), followed by plantation liquidation (15.7%) and field transport of chips (7.7%).

When mineral fertilizers (F) were used for poplar fertilisation, GHG emission from the production process (poplar cultivation) was $474 \text{ kg ha}^{-1} \text{ year}^{-1} \text{ CO}_2 \text{ eq.}$ (Table 4). However, a large degree of organic carbon sequestration at the plantation was observed ($505 \text{ kg ha}^{-1} \text{ year}^{-1} \text{ CO}_2 \text{ eq.}$), which was in excess of the GHG emission. Therefore, the net emission was negative: $-31.07 \text{ kg ha}^{-1} \text{ year}^{-1} \text{ CO}_2 \text{ eq.}$ When calculated per 1 Mg of dry biomass and 1 GJ, the net emission was -3.37 and $-0.20 \text{ kg CO}_2 \text{ eq.}$, respectively (Fig. 2). The biomass harvest contribution to the climate change was 42% and the production of mineral fertilizers was responsible for the second largest emission (39%). Emission from the production processes ($415 \text{ kg ha}^{-1} \text{ year}^{-1} \text{ CO}_2 \text{ eq.}$) in variant L was close to F, but GHG emission in lignin production was lower than in the production of mineral fertilizers. Moreover, more organic carbon was supplied with lignin, which was partly sequestered in soil.

Table 1
Data inventory of poplar production.

Operation	Tractor/Harvester Name	Machinery Name	Diesel fuel (kg ha ⁻¹)	Comments	Source data
Cuttings preparation	Ursus C360 3P 48HP	Propelled circular saw	1.26	11,000 Cuttings from 0.05 ha of the plantation fertilized with mineral NPK, 0.002 kWh electricity per cutting used	This study, estimation
Spraying (1)	New Holland TM 130 HP	Krukowiak sprayer, working width 18 m	2.04	Glyphosate, Roundup 360 SL, 5 l ha ⁻¹	This study
Winter ploughing	New Holland TM 175 HP	Kverneland PG 100 plough, working width 2 m	29.30	5-ridge plough, ploughing depth 30 cm	This study
Lignin fertilisation	New Holland TM 130 HP	Rauch 3,0 t spreader, working width 18 m	20.36	Application of lignin, 13.3 Mg ha ⁻¹ , no	This study (Bernier et al., 2013)
Disking (2x)		Kverneland disk harrow, working width 4 m	17.96	2 x coverage	This study
Harrowing (2x)		Harrow, working width 6 m	11.20	2 x coverage	This study
Marking planting spots		3-tooth subsoiled U435/1 KRET	24.44		This study
Manual planting	n/a			Planting density 11,111 cuttings per ha	This study
Spraying (2)	New Holland TM 130 HP	Krukowiak sprayer, working width 18 m	2.04	Soil-applied herbicide, Guardian Complete Mix 664 SE, 3.5 l ha ⁻¹ , for this study average data for herbicides was taken from Ecoinvent	This study, Ecoinvent
Mechanical weeding (3x)	New Holland TM 90 HP	Mechanical weeder P 430/2, working width 3 m	21.09	3 x coverage	This study
Mineral fertilisation	New Holland TM 130 HP	Rauch 3,0 t spreader, working width 18 m	13.24	Mineral fertilisation in spring 2011, N–90; P ₂ O ₅ –30; K ₂ O–60 kg ha ⁻¹	Own research, (Stolarski et al., 2014), Ecoinvent
Liquidation of plantation	New Holland TM 175 HP	Rototiller FV 4088, working width 40 cm	117.21	Breaking up larger rootstocks along rows	Own research, (Stolarski et al., 2014)
Harvesting	Claas Jaguar 830	–	126.1–241.8*	*depending on the yield of a SRWC species, average productivity of harvester 20 ton of chips per hour	Own research, (Stolarski et al., 2014)
Field transport	New Holland TM 130 HP	T 169/2 tractor trailer, loading capacity: 4 tons of chips	tkm**	** Input in tonne × kilometre (tkm) depending on the yield	Own research, (Stolarski et al., 2014), Ecoinvent

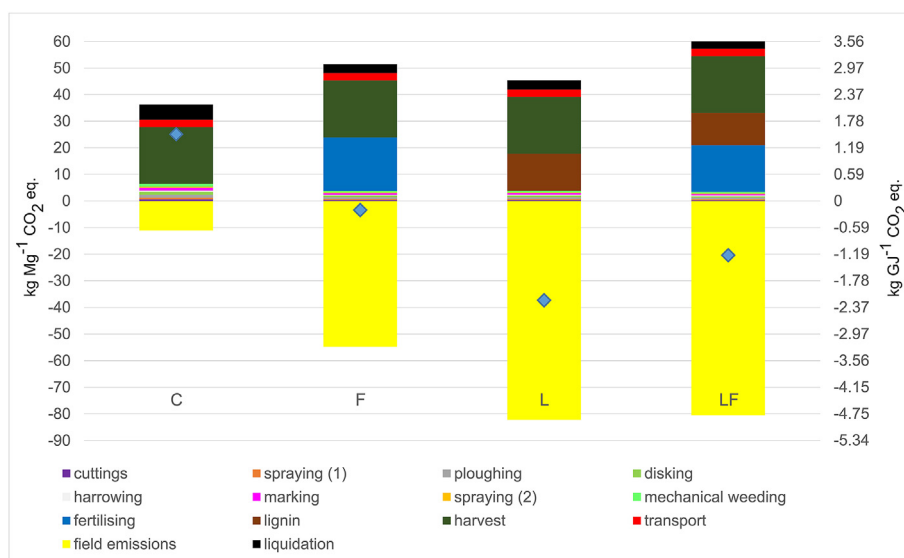


Fig. 2. Greenhouse gases emission (kg CO₂ eq.) from poplar cultivation depending on the fertilisation option; the rhombus sign denotes the net emission.

Therefore, negative net GHG emission per 1 ha was recorded: $-338 \text{ kg ha}^{-1} \text{ year}^{-1} \text{ CO}_2 \text{ eq.}$ (Table 4). When calculated per 1 Mg of dry biomass and 1 GJ of energy in biomass (Fig. 2), it was $-37.0 \text{ kg Mg}^{-1} \text{ CO}_2 \text{ eq.}$ and $-2.19 \text{ kg GJ}^{-1} \text{ CO}_2 \text{ eq.}$, respectively. As in variants C and F, biomass harvest was the stage of production

with the largest contribution to GHG emissions (47.2%); production and spreading of lignin contributed 31% and plantation liquidation contributed 6.2%. Although the combined use of lignin and mineral fertilisation (LF) resulted in the highest yield of biomass and energy (Table 2), it does not result in the lowest GHG emission, either per

Table 2
Poplar biomass yield and its energy value throughout the plantation life cycle (20 years) for various methods of soil enrichment based on (Stolarski et al., 2015, 2016a).

Soil amendment	Total biomass yield throughout a plantation life cycle		Total energy yield throughout a plantation life cycle
	(Mg ha ⁻¹ f.m.)	(Mg ha ⁻¹ d.m.)	(GJ ha ⁻¹)
Control (C)	247.3	109.6	1850
Mineral fertilisation (F)	416.2	184.2	3102
Lignin (L)	414.35	183.2	3090
Lignin + mineral fertilisation (LF)	474.35	209.8	3534

1 ha (–213 kg ha⁻¹ year⁻¹ CO₂ eq.) or when calculated for a biomass or energy unit (–20.3 kg Mg⁻¹ CO₂ eq. and –1.20 kg GJ⁻¹ CO₂ eq., respectively) (Table 4, Fig. 2). However, a combination of these fertilisation methods resulted in lower emission in the climate change category than in variants F and C. Sequestration of organic carbon in variant LF was higher than in the other variants, but this benefit was eliminated by the high GHG emission from the production of mineral fertilizers and the production and spreading of lignin (Table 4, Fig. 2). These two stages of biomass production combined accounted for half of the emission of the carbon dioxide equivalents. Biomass harvest also had a high environmental impact in this category (35.5% share in GHG).

The lowest emission of PM10 equivalents, calculated per 1 Mg of dry biomass, was determined for the cultivation of poplar with lignin as fertilizer (0.253 kg PM10 eq.) (Fig. 3). Emission was higher by approx. 25% and ranged from 0.315 to 0.320 kg Mg⁻¹ d.m. PM10 eq. in the other variants. Field emission was responsible for 41–55%

of the contribution of this impact category in all the cultivation variants. A large contribution (28–35%) was also determined for harvest. An effect of the production of lignin (contribution of 7–10%) can be observed in the variants in which lignin was applied (L and LF). The production of mineral fertilizers in the F and LF variants also affected particulate matter formation (contribution of 9 and 8%, respectively).

The application of mineral fertilizers (mainly ammonium nitrate) in the F and LF variants significantly increased the terrestrial acidification – more than 2.5-fold compared to the control, which was the most environmentally-friendly (0.27 kg Mg⁻¹ d.m. SO₂ eq.) (Fig. 4). The application of lignin alone increased the emission in this category by 19% compared to C. The production and application (field emission) of mineral fertilizers and lignin in variants F and LF contributed 66% and 80% to terrestrial acidification. The highest contribution in this impact category was determined for biomass harvest: 54% and 64% for lignin fertilisation (L) and no fertilisation

Table 3
Data taken for the calculation of field emissions from poplar production.

Crop	Parameters	Value	Unit	Source data and notes
Spring barley (reference crop)	Grain yield (Y)	3.36	Mg·ha ⁻¹ d.m.	Mean yield in Poland in 2011–2013 (Central Statistical Office, 2014)
Poplar	α	0.45		Taghizadeh-Toosi et al. (2014)
	β	0.17		Taghizadeh-Toosi et al. (2014)
	ε	460	kg C Mg ⁻¹ d.m.	Parajuli et al. (2017b)
	Biomass yield (Y)	see Table 2		This study
	Total annual leaf litter fall (crop residues)	4.02 ± 1.04 (mean ± SD)	Mg ha ⁻¹ d.m.	This study
	OC content in litter	436.0 ± 9.0 (mean ± SD)	kg C Mg ⁻¹ d.m.	This study
	α	0.72		This study
	β	0.24		This study
	ε	526.9 ± 3.0 (mean ± SD)	kg C Mg ⁻¹ d.m.	This study
	OC content in lignin	61.72	% f.m.	Own research, (Stolarski et al., 2015)
	R _{AG}	0.39		This study
	R _{BG}	0.44		Calculation based on data taken from Berhongeray et al. (2015)
	EF _{default} for N ₂ O from N leaching/runoff	0.0075	kg N ₂ O-N kg ⁻¹ N	Eggleston et al. (2006)
	EF _{default} for N ₂ O from the other sources of nitrogen	0.01	kg N ₂ O-N kg ⁻¹ N	Eggleston et al. (2006)
	N _{AD}	3.8	kg ha ⁻¹ N	Mean value for the north-east of Poland (Chief Inspectorate of Environmental Protection, 2017)
	C:N ratio in soil	12.5		Smólczyński et al. (2011)
	EF _{TS} for NH ₃ from fertilizers	0.016	kg NH ₃ ·kg ⁻¹ N _{input}	European Environment Agency (2016)
	EF _{default} for NO _x from fertilizers (as NO ₂)	0.04	kg NO ₂ ·kg ⁻¹ N _{input}	European Environment Agency (2016)
	EF _{default} for NMVOC	0.06	kg ha ⁻¹	European Environment Agency (2016)
	EF _{TS} for PM10 from soil cultivation	2.25	kg ha ⁻¹	European Environment Agency (2016)
	EF _{TS} for PM2.5 from soil cultivation	0.12	kg ha ⁻¹	European Environment Agency (2016)
	EF _{default} for phosphates leached following use of mineral fertilizers	0.01	kg PO ₄ ³⁻ kg ⁻¹ P _{applied}	Iriarte et al. (2010)

α – harvest index of main crop product relative to aboveground biomass, β – root biomass carbon as proportion of yield of main crop product, ε – concentration of C in biomass, R_{AG} – ratio of above-ground residues dry matter to harvested yield d.m. for crop, R_{BG} – ratio of below-ground residues dry matter to harvested yield d.m. for crop (root:shoot ratio), EF_{default} – default emission factor, N_{AD} – nitrogen deposition with atmospheric precipitation, EF_{TS} – technology-specific emission factor.

Table 4
Greenhouse gases emission from 1 ha of poplar cultivation depending on the fertilisation option ($\text{kg ha}^{-1} \text{ year}^{-1} \text{ CO}_2 \text{ eq.}$).

Fertilisation	Cuttings preparation	Spraying (1)	Ploughing	Disking	Harrowing	Marking	Spraying (2)	Mechanical weeding	Fertilising	Lignin production and application	Harvest	Transport	Liquidation	Subtotal (without C sequestration)	Field emissions	Total
C	3.31	3.25	6.64	5.38	3.11	5.54	2.42	5.86	0.00	0.00	116.97	15.28	31.18	198.95	-61.00	137.95
F	3.31	3.25	6.64	5.38	3.11	5.54	2.42	5.86	184.68	0.00	196.84	25.71	31.18	473.93	-505.00	-31.07
L	3.31	3.25	6.64	5.38	3.11	5.54	2.42	5.86	0.00	127.01	195.91	25.60	31.18	415.22	-753.70	-338.48
LF	3.31	3.25	6.64	5.38	3.11	5.54	2.42	5.86	184.68	127.01	224.31	29.31	31.18	632.00	-844.50	-212.50

(C), respectively. It is noteworthy that despite a higher input per 1 ha in variant LF, total emission per 1 Mg of dry biomass was nearly the same as in the F variant and was associated with a lower yield in the second cultivation variant (Table 2, Fig. 4).

The highest impact on freshwater eutrophication was found for poplar production in the LF variant ($0.027 \text{ kg Mg}^{-1} \text{ d.m. P eq.}$) (Fig. 5). A large contribution in this category was determined for the production of fertilizers (36%) and lignin (34%). In the first case, the large emission originated from production of phosphoric acid, used in turn in the production of triple superphosphate and sodium hydroxide used in the production of lignin. Harvest contributed 12%, and field emission contributed 9% in this impact category. Variants L and F were also less beneficial to the environment than C and the emission of phosphorus equivalent was 0.016 and $0.020 \text{ kg Mg}^{-1} \text{ d.m.}$, respectively. The production of fertilizers in these variants contributed 60% in the category of freshwater eutrophication. Biomass harvest had the greatest contribution to emission (46%) in the control ($0.007 \text{ kg Mg}^{-1} \text{ d.m. P eq.}$).

The greatest impact on human toxicity per 1 Mg of dry biomass was determined in variant LF ($19.8 \text{ kg Mg}^{-1} \text{ 1,4-DB eq.}$) (Fig. 6). Up to 63% in this category of impact was contributed by the production of lignin and mineral fertilizers and 24% by the biomass harvest (mainly machine production). Similar, although lower, values were found for poplar production in variant L ($18.3 \text{ kg Mg}^{-1} \text{ d.m. 1,4-DB eq.}$). The largest contribution to emission was determined for the production of lignin (58%), followed by harvest (24%). Emission in variant F was lower by 78% than in LF, and the highest environmental impact in this category was observed in harvest (43%) and fertilizer production (32%). The control had the least environmental impact ($8.88 \text{ kg Mg}^{-1} \text{ d.m. 1,4-DB eq.}$) with the highest contribution from the biomass harvest, liquidation of the plantation and field transport of chips and, in particular, from the production of machines needed for these cultivation procedures.

The smallest contribution per 1 Mg d.m. in the category of terrestrial ecotoxicity was determined in poplar production without fertilisation (below $0.005 \text{ kg Mg}^{-1} \text{ 1,4-DB eq.}$) (Fig. 7) and impact on terrestrial toxicity increased proportionally in the sequence: F, L and LF, by 14%, 37% and 56%, respectively. The highest contribution in this impact category in variants L and LF was determined in lignin production (42% and 32%, respectively), followed by biomass harvest (30 and 26%, respectively). Harvest had the greatest impact on terrestrial toxicity (36%) when poplar was fertilized only with mineral fertilizers (F), followed by the production of mineral fertilizers (30%), especially ammonium nitrate. Biomass harvest contributed 41% to terrestrial toxicity in variant C and the impact of production and application of glyphosate was also high (26%).

The highest impact on freshwater ecotoxicity was found in the variant of biomass production in which lignin and mineral fertilizers were used ($0.36 \text{ kg Mg}^{-1} \text{ d.m. 1,4-DB eq.}$). A slightly lower impact was calculated in variant L (Fig. 8). As in other categories of toxicity, the largest contribution was determined for the production of lignin (production of sodium hydroxide), which accounted for 49% and 40% in variants L and LF, respectively. Harvest was another process with a high impact (23–25%). A similar impact on freshwater ecotoxicity was determined in variants C and F; when calculated per 1 Mg of dry biomass it was $0.23 \text{ kg Mg}^{-1} \text{ d.m. 1,4-DB eq.}$ The harvest accounted for 36–37% of the environmental impact in this category. The second largest contribution in variant F was determined for fertilisation (25%) and in variant C - for the production and application of glyphosate (26%).

The highest impact per 1 Mg d.m. in the fossil depletion category was determined when lignin and mineral fertilisation were applied in combination ($17.12 \text{ kg Mg}^{-1} \text{ oil eq.}$) (Fig. 9). Fossil depletion in variants L and F was smaller by 15% than in LF. The smallest impact

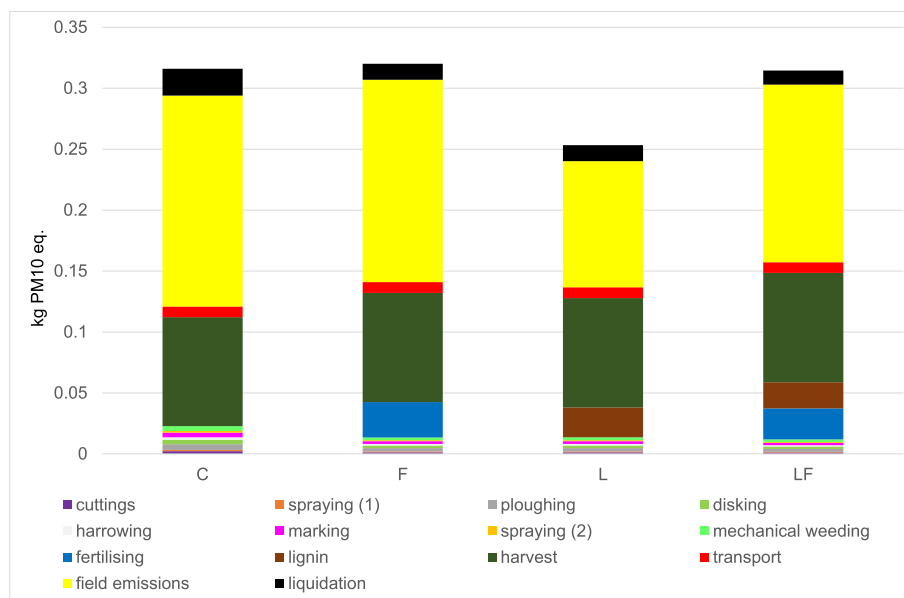


Fig. 3. Particulate matter formation (per 1 Mg d.m.) in the poplar cultivation depending on the fertilisation option.

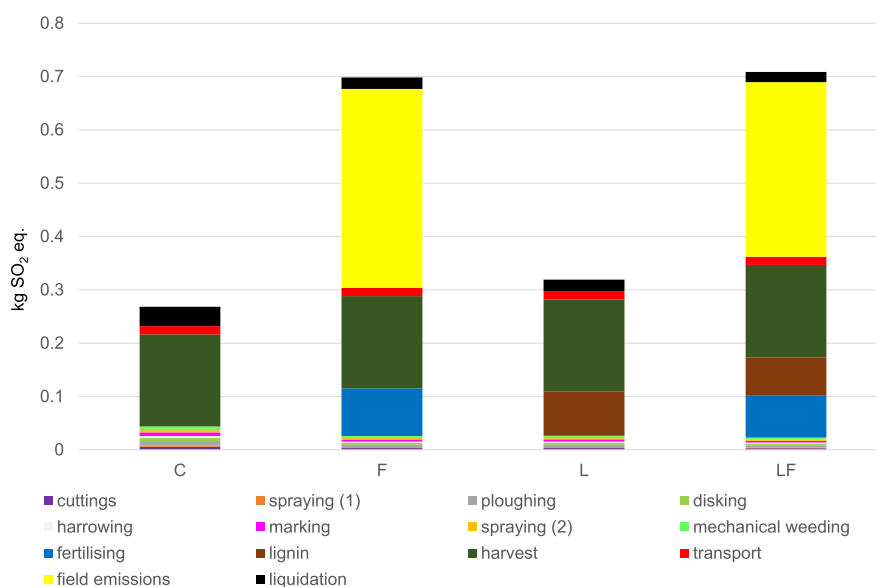


Fig. 4. Terrestrial acidification (per 1 Mg d.m.) in the poplar cultivation depending on the soil enrichment.

in this category was determined in the variant in which poplar was grown with no fertilisation ($12.45 \text{ kg Mg}^{-1} \text{ d.m. oil eq.}$). Poplar harvest had the greatest contribution in this category in all cultivation options: from 43% to 59%, for LF and C, respectively. A considerable portion of the input was consumed for the production of sodium hydroxide (lignin production) in the L and F variants and for production of the nitrogen fertilizer in F; they accounted for 26% of contribution to fossil depletion. The plantation liquidation had the second-largest environmental impact (16%) in the cultivation with no fertilisation (C).

3.2. Normalization results

Fig. 10 shows the impact assessment results expressed per dry tonne and per 1 GJ normalized using ReCiPe's European

hierarchical version. In all cultivation variants except C, a very high normalized score was determined for freshwater eutrophication (Fig. 10). A high score was also determined in variants L and LF in freshwater and human ecotoxicity. The normalized score was similar in the particulate matter formation and terrestrial acidification, although with a considerable drop of the impact of variants C and L in the latter category. A low impact of poplar cultivation was determined for fossil depletion and was nearly negligible for terrestrial ecotoxicity. A low normalized score was also calculated for climate change compared to other impact categories.

3.3. Discussion and conclusion

The results of the life cycle assessment have shown that each of the methods of the poplar plantation fertilisation (F, L and LF)

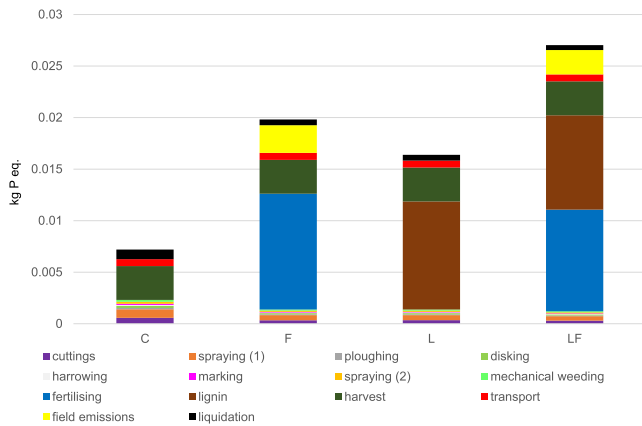


Fig. 5. Freshwater eutrophication (per 1 Mg d.m.) in the poplar cultivation depending on the soil enrichment.

increased carbon fixing in soil. Therefore, poplar production “to the farm gate” was characterized by negative emission of greenhouse gas. Only in poplar cultivation with no fertilizers was GHG emission positive, although it was also low ($25.2 \text{ kg Mg}^{-1} \text{ d.m. CO}_2 \text{ eq.}$). Schweier et al. (2016) studied poplar cultivation without the fertilisation applied and without the biomass transport to the conversion site gate and found GHG emission to be $8.88\text{--}10.49 \text{ kg Mg}^{-1} \text{ d.m. CO}_2 \text{ eq.}$ and it increased to $90.56\text{--}98.81 \text{ kg Mg}^{-1} \text{ d.m. CO}_2 \text{ eq.}$ in variants with irrigation and fertilisation. However, this study disregarded carbon sequestration in soil. Moreover, poplar grown on marginal soil gave a lower yield compared to the results of this study. However, without sequestration, the results in this study would be smaller for variants F, L and LF ($51.5\text{--}60.2 \text{ kg Mg}^{-1} \text{ d.m. CO}_2 \text{ eq.}$). Gasol et al. (2009) reports a study in which carbon sequestration at the plantation was not taken into account; in the study, GHG emission during the 16 years of the plantation life, to the farm gate, was $5122\text{--}5274 \text{ kg ha}^{-1} \text{ CO}_2 \text{ eq.}$ Emission from cultivation of short and medium rotation poplar was slightly

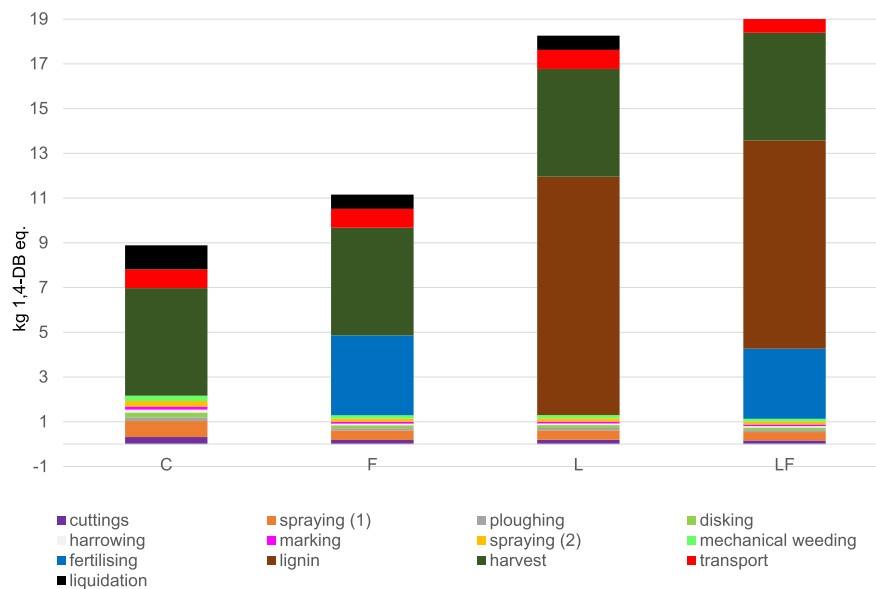


Fig. 6. Human toxicity (per 1 Mg d.m.) in the poplar cultivation depending on the soil enrichment.

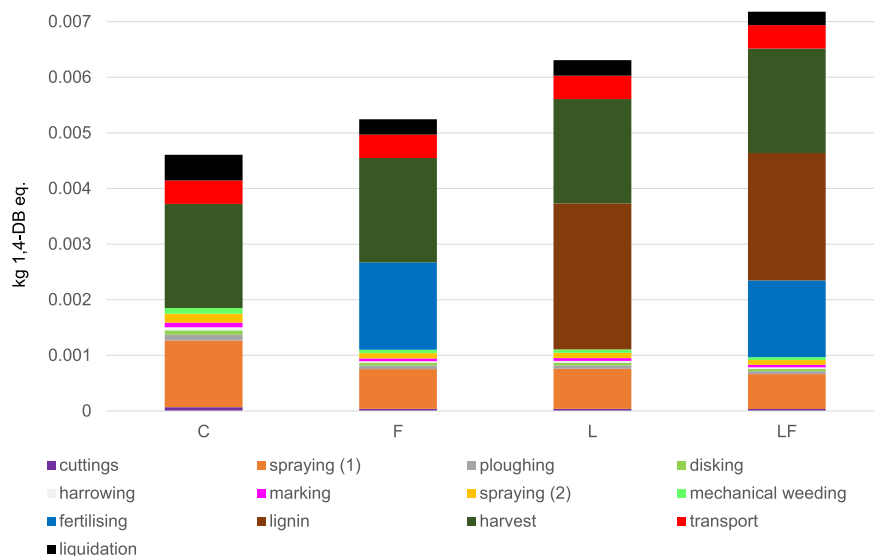


Fig. 7. Terrestrial ecotoxicity (per 1 Mg d.m.) in the poplar cultivation depending on the soil enrichment.

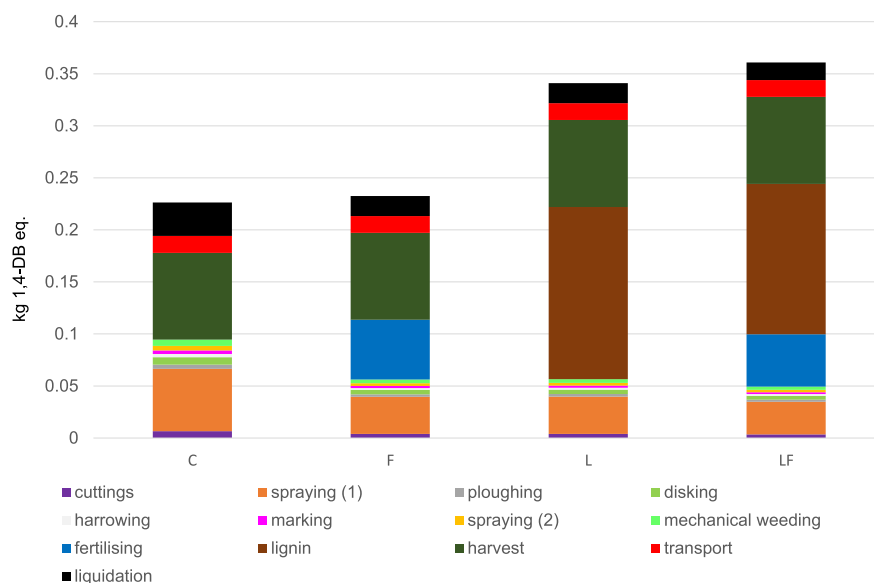


Fig. 8. Freshwater ecotoxicity (per 1 Mg d.m.) in the poplar cultivation depending on the soil enrichment.

higher—5660 and 5307 kg ha⁻¹ CO₂ eq., respectively. When carbon sequestration in poplar biomass was taken into account, it was slightly lower than in this study (−361.1 and −375.3 Mg ha⁻¹ CO₂ eq.).

Furthermore, in the authors' earlier LCA studies on short rotation willow coppice, GHG emission (with carbon sequestration taken into account) per 1 ha was 5036–5752 kg ha⁻¹ CO₂ eq. or 19–97 kg Mg⁻¹ d.m. CO₂ eq. and it depended on biomass yield (Krzyżaniak et al., 2016). Other studies on willow have shown that GHG emission can also be negative (from −2.7 to −6.9 kg GJ⁻¹ CO₂ eq.), which is caused by large carbon sequestration in soil (Goglio and Owende, 2009). Obviously, the carbon footprint is not connected only to biomass yield, lignocellulosic species or fertilisation method, but also with changes in agricultural management; for

example, enhancing rotation complexity or changing from conventional tillage to no-till management to sequester more carbon in the soil (West and Post, 2002). Thus, these practices also mitigate the global warming effect of agricultural systems.

The application of mineral and organic (lignin) fertilisation in the current study affected carbon fixing by the poplar plantation. Similar findings were recorded in a study by Murphy et al. (2013) in which the use of sludge in a plantation of giant miscanthus reduced GHG emission by 23–33%. Meanwhile, Krzyżaniak et al. (2018) in LCA of Virginia mallow cultivation found that use of dried and torrefied digestates resulted in a decrease in greenhouse gas emissions compared to cultivation with no fertilizers. On the other hand, mineral fertilisation and wet digestate cultivation variants emitted more GHG than the base scenario.

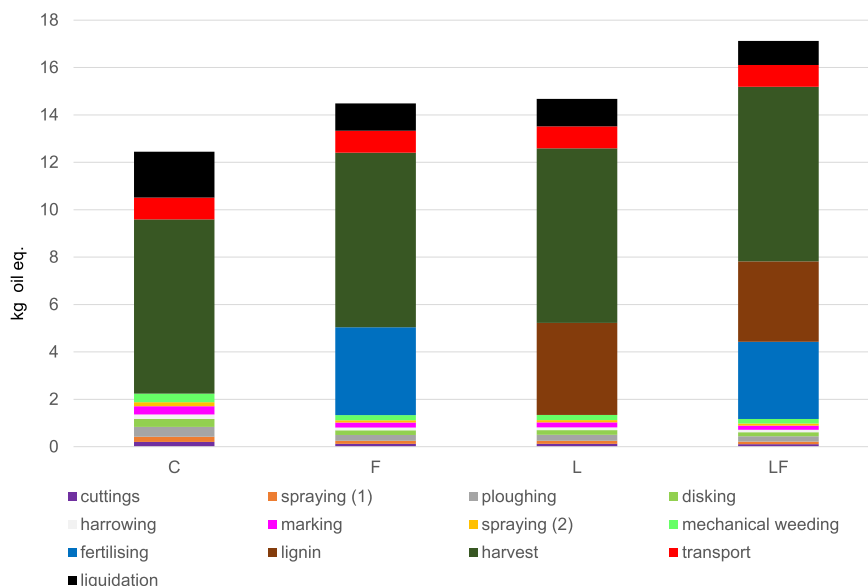


Fig. 9. Fossil depletion (per 1 Mg d.m.) in the poplar cultivation depending on the soil enrichment.

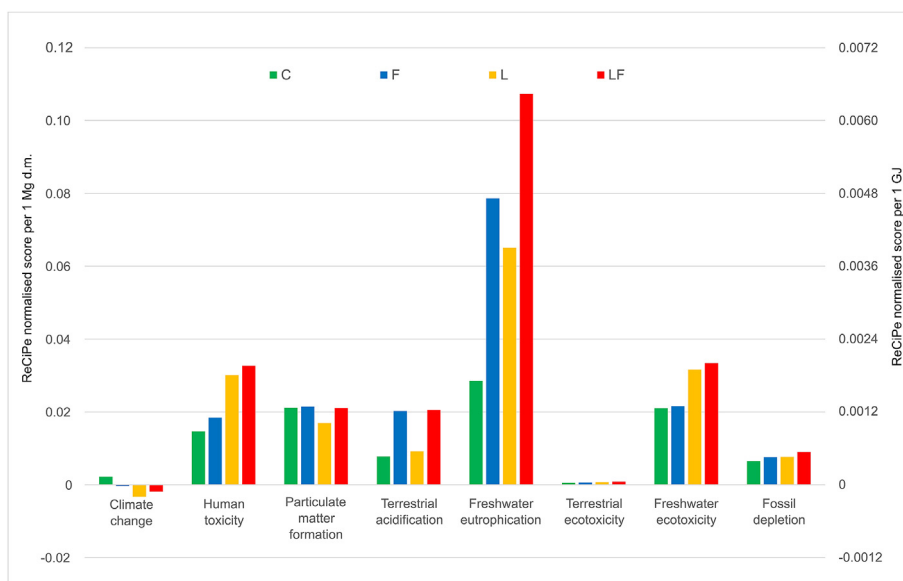


Fig. 10. Results of normalization of poplar production, using the ReCiPe midpoint impact assessment method (hierarchical version with European normalization).

The low emission of carbon dioxide equivalents is a great advantage in crops intended for bio-based industries. However, it should be emphasized that the application of mineral fertilizers and lignin usually had an adverse environmental impact in most of the impact categories. The effect of fertilisation was particularly marked in the freshwater eutrophication category. But emission in this case was lower than in other studies, in particular compared to plantations in which considerable amounts of nitrogen and phosphorus fertilizers were used, or in which a number of plant protection products were used, which affect all the categories of toxicity (Chatzisyneon et al., 2017; Krzyżaniak et al., 2016, 2018; Murphy et al., 2013). This analysis may indicate that - from an environmental point of view - poplar plantations should not be fertilized with mineral fertilizers and lignin. Even a higher yield of dry biomass did not result in a lower emission per unit of biomass produced. However, in practice, the environmental aspect should be reconciled with the economic aspect. The authors' earlier studies showed that the highest revenue was earned from poplar production in variants LF and L (193.9 and 191.2 € ha⁻¹ year⁻¹, respectively) and only 64.5 € ha⁻¹ year⁻¹ from control. Although NPV and IRR indices were favourable for all the three variants of fertilisation, the most profitable variants are usually applied by farmers (Stolarski et al., 2017b). The current analyses indicates that lignin can be recommended as the optimum method of fertilising a plantation in terms of its environmental impact, which also brings considerable revenue to the biomass producer. A commonly applied variant, i.e. using only mineral fertilisation in a plantation, is much less beneficial to the environment, especially in regard to freshwater eutrophication and terrestrial acidification. On the other hand, the use of both types of fertilizers simultaneously (LF) is not recommended due to high freshwater eutrophication, high terrestrial acidification, human and freshwater ecotoxicity and the highest depletion of fossil resources.

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